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# **Novel Aluminum-based High-Q Cold RF Resonators for ADMX**

Katsuya Yonehara

ADMX RF resonator workshop at LLNL

24-28<sup>th</sup> August, 2015

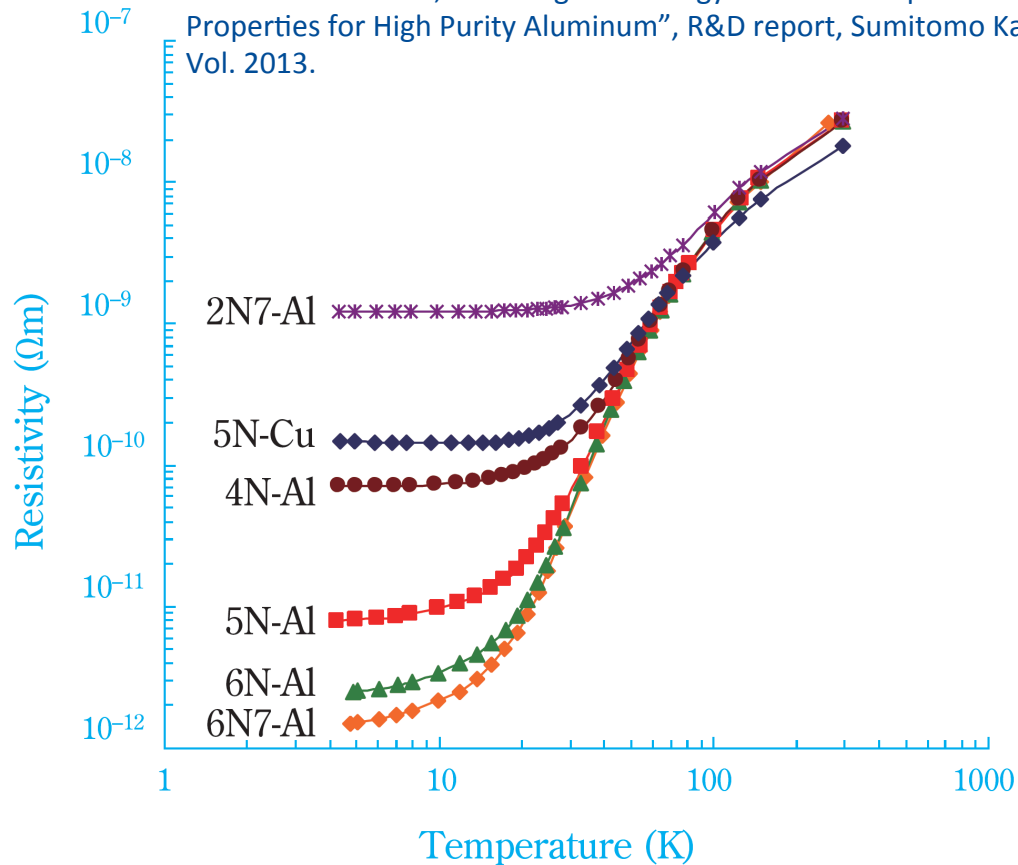
# Attractive metal, high-purity Aluminum

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- Improved aluminum refining techniques now provide high-quality, cost effective high-purity aluminum samples
- High-purity aluminum shows extremely low electric resistivity at low temperatures in strong magnetic fields
- High energy physics opportunities now at hand motivate a targeted R&D program to fabricate and evaluate resonating cavities using very high purity aluminum at low temperatures in strong magnetic fields
  - Axion detector resonator

# DC electric resistivity of Aluminum and Copper

H. Hoshikawa et al., "Refining Technology and Low Temperature Properties for High Purity Aluminum", R&D report, Sumitomo Kagaku Vol. 1913.



5N = 99.999 %  
6N7 = 99.99997 %

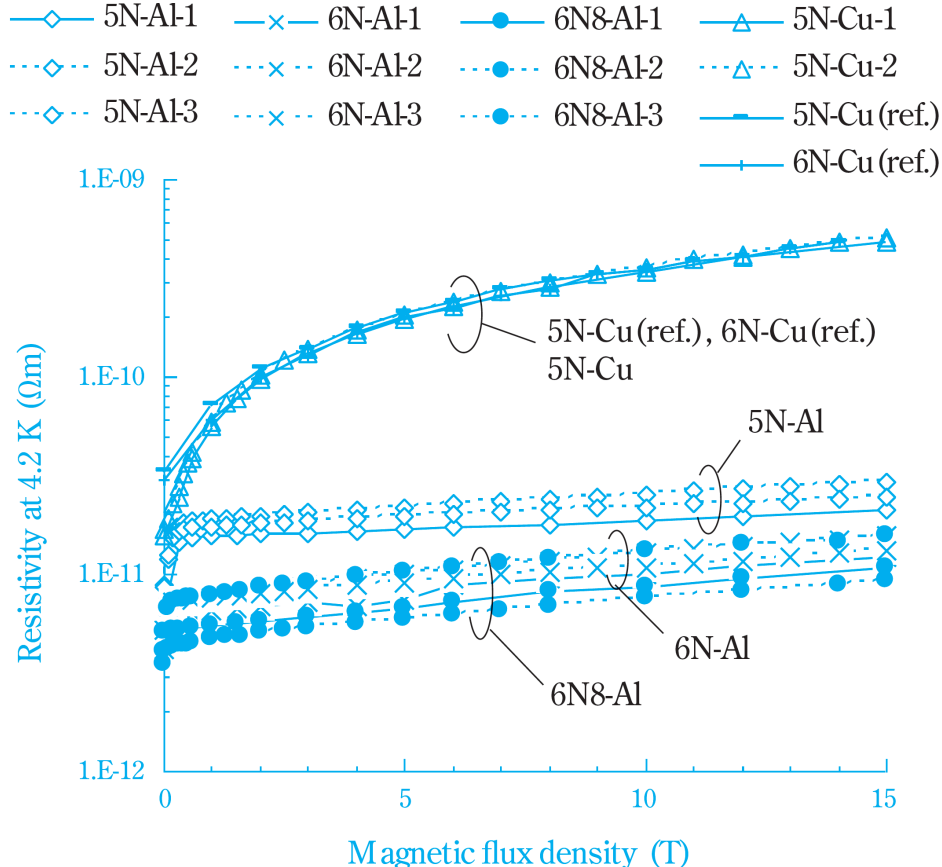
- Resistivity of 5N-Al is one order of magnitude smaller than 5N-Cu
- 6N7-Al is available as a commercial product that shows two orders of magnitude lower resistivity than 5N-Cu
- Al cost about half from the same purity Cu



Al ingot purified through ultra-high vacuum melting

# DC electric resistivity of Al and Cu in strong magnetic fields

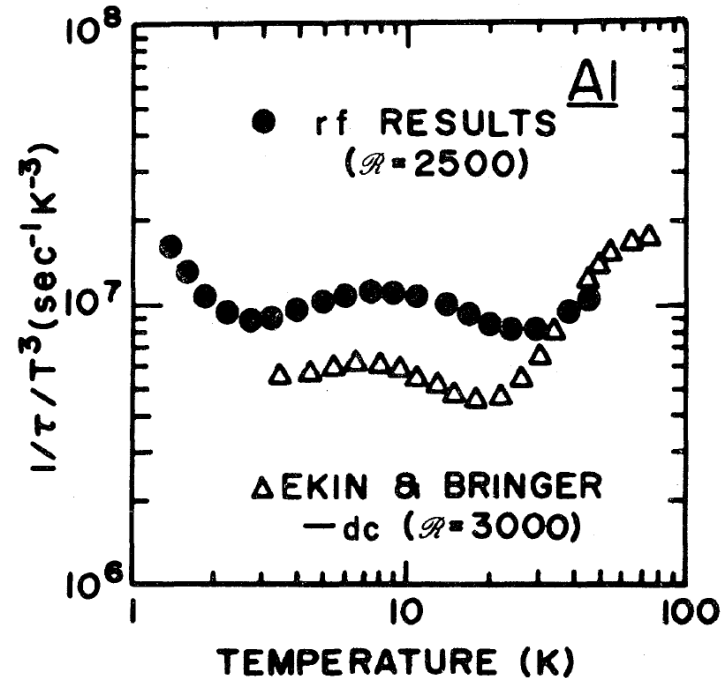
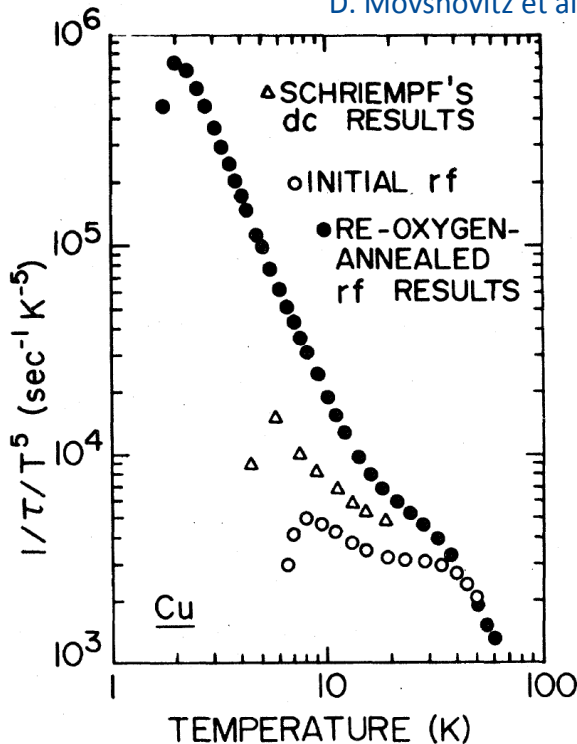
H. Hoshikawa et al., "Refining Technology and Low Temperature Properties for High Purity Aluminum", R&D report, Sumitomo Kagaku Vol. 2013.



- Resistivity of copper increases quadratic as a function of external magnetic field strength
- It is called magneto-resistivity
- Magneto-resistivity of aluminum is saturated in a strong magnetic field

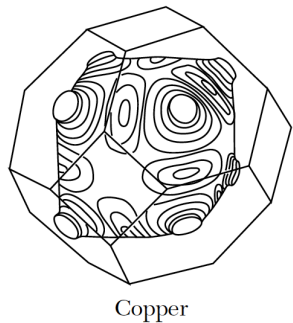
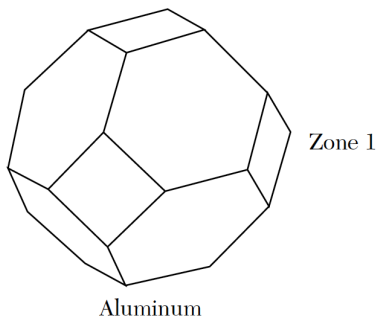
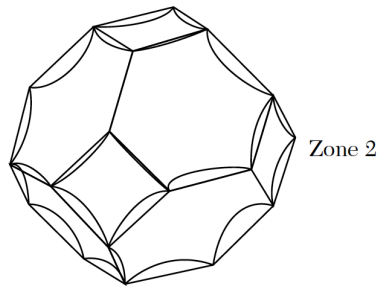
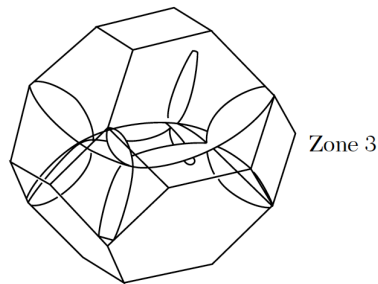
# AC electric resistivity of Al and Cu

D. Movshovitz et al., Phys. Rev. B41, 10503, 1990



- This is only experimental result I found
- $1/\tau$  ( $\propto$  resistivity in Drude theory) of Cu significantly increases (take a part from the DC measurement) at low temperature which shows an anomalous skin effect
- While  $1/\tau$  is a constant (close to the DC measurement) in Al conductor

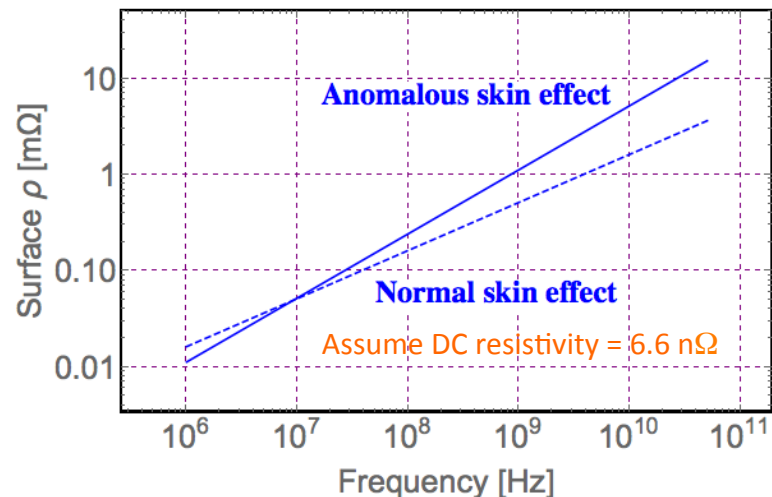
# Electron conductivity model



Aluminum

- Most characteristics of metal is represented by Fermi surface (k-space)
- Cu has one conductive electron while Al has three
- Since the Fermi surface of Cu is close to a sphere some properties can be estimated analytically

Example: surface resistivity of Cu conductor



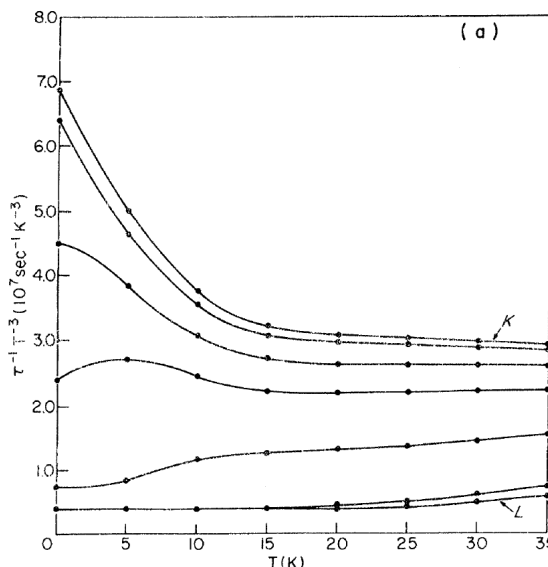
# Theoretical investigation of conductivity in Aluminum

- Electron conductivity of Al is more complicate
- Relaxation rate due to an electron-phonon interaction

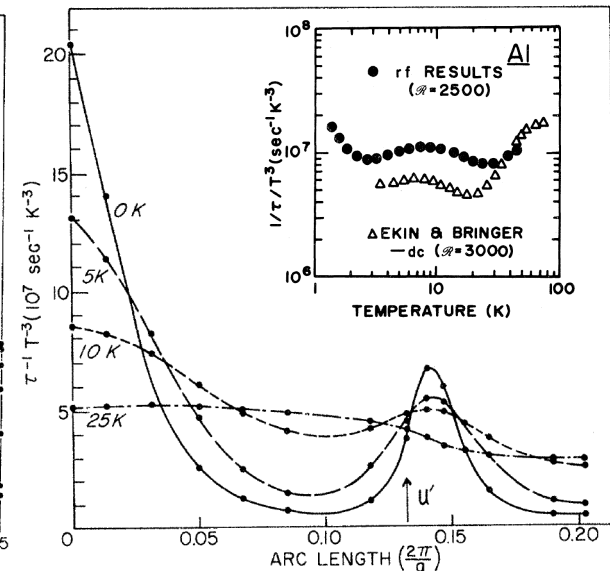
$$\tau^{-1}(\vec{k}, \varepsilon = 0) = \frac{1}{\pi^2} \int \frac{dS'}{\hbar |\vec{v}'|} \sum_{\sigma} \left| g_{\sigma}(\vec{k}, \vec{k}') \right|^2 f(\hbar \omega_{Q\sigma} / k_B T)$$

Scattering amp      Density function

Relaxation rate in second zone Fermi surface



Relaxation rate in third zone Fermi surface



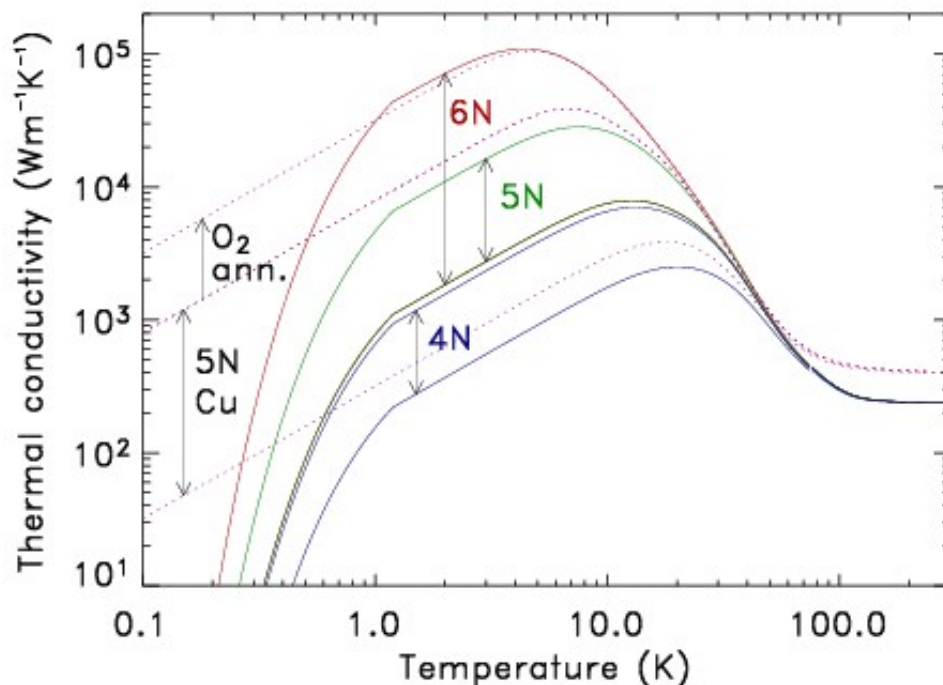
D.P. Love et al., Phys. Rev. B26, 5577, 1982

- (a) Meshed second-zone Fermi surface  
(b) Meshed second- and third-zone Fermi surface in computer simulation

- Model shows qualitative agreement with experiment

# Thermal conductivity of Aluminum and Copper

A.L. Woodcraft, Cryogenics 45(9) 626-636, 2005



- 6N-Al shows the highest thermal conductivity
- Kink point at 1.2 K is because Al becomes superconducting
- Thermal conductivity of copper will be worse in stronger magnetic fields according to the Wiedemann-Franz law



# High-Q cold RF resonator for ADMX

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- The present ADMX resonator is made of copper. It operates at 100 mK in an 8-Tesla solenoid field with resonant frequencies 0.5-2 GHz. Because the magneto-resistivity and the anomalous skin effect are prominent in the copper resonator, the available Q-factor is  $<10^5$ .
- If the AC resistivity of high-purity aluminum in strong magnetic fields is kept as low as previous measurements imply, the Q-factor could be an order of magnitude higher than the copper resonator, resulting in an order of magnitude reduction in the integration time required to detect the axion signal.

# Proposed 3-yrs project for studying of material properties of high-purity aluminum

- DC electric resistivity and thermal conductivity test
- AC electric resistivity test
- Prototype High-Q cold RF resonator

## Time table (3 year plan)

	FY16				FY17				FY18			
	Oct	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct	Jan	Apr	Jul
Team formation	Dark blue											
Teslatron@TD	Dark blue	Dark blue	Dark blue	Dark blue ← DC								
		Dark blue	Dark blue	Dark blue	Dark blue ← Thermal	Dark blue	Dark blue	Dark blue				
SCM1@NHMFL				Dark blue	Dark blue	Dark blue	Dark blue	Dark blue ← AC				
Prototype RF							Dark blue	Dark blue	Dark blue	Dark blue	Dark blue	Dark blue

Dark blue: Preparation

Orange: Cold test

Light blue: Contingency

# DC electric resistivity and thermal conductivity tests

DC electric resistivity measurements are required to check the sample quality and to use the result for theoretical investigations of electron conductivity compared with the AC result

## High-field cold facility in Technical Division at Fermilab



Teslatron  
(0-14 Tesla)

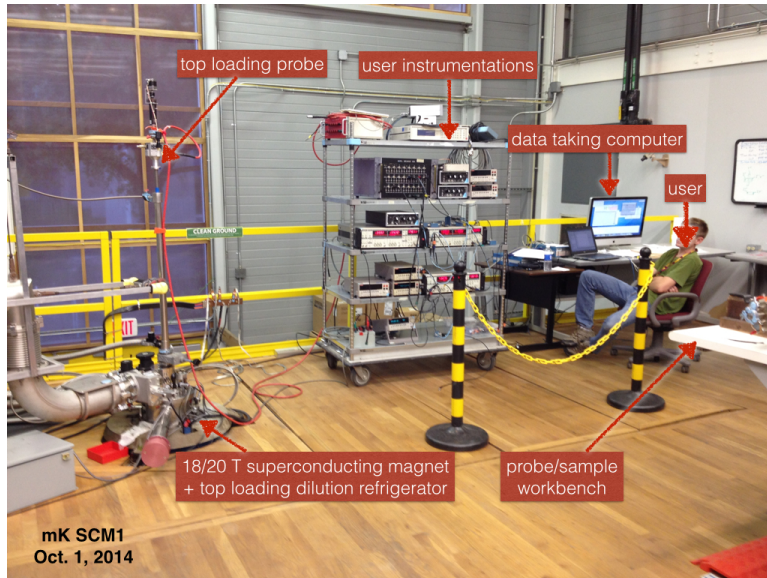


Inserts for DC resistivity test  
(300 – 1.9 Kelvin)



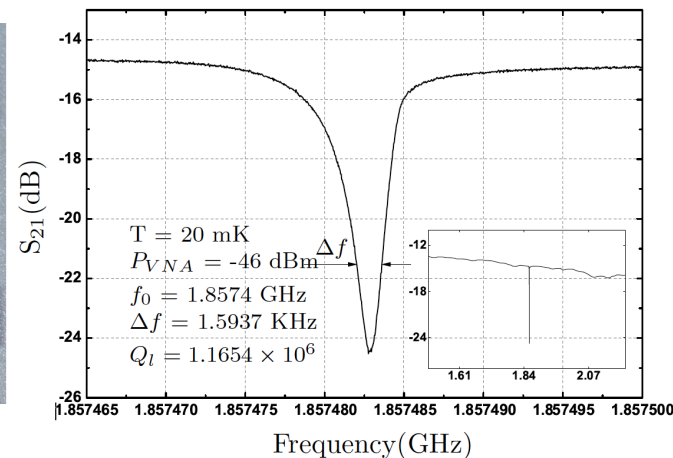
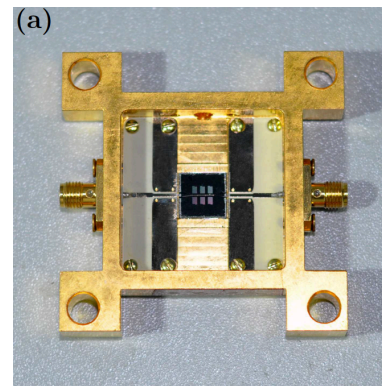
Instruments  
(nano-voltmeter,  
low jitter current source,  
temperature sensor)

# AC electric resistivity



SCM-1  
(0-20 Tesla  
300-0.01 Kelvin)

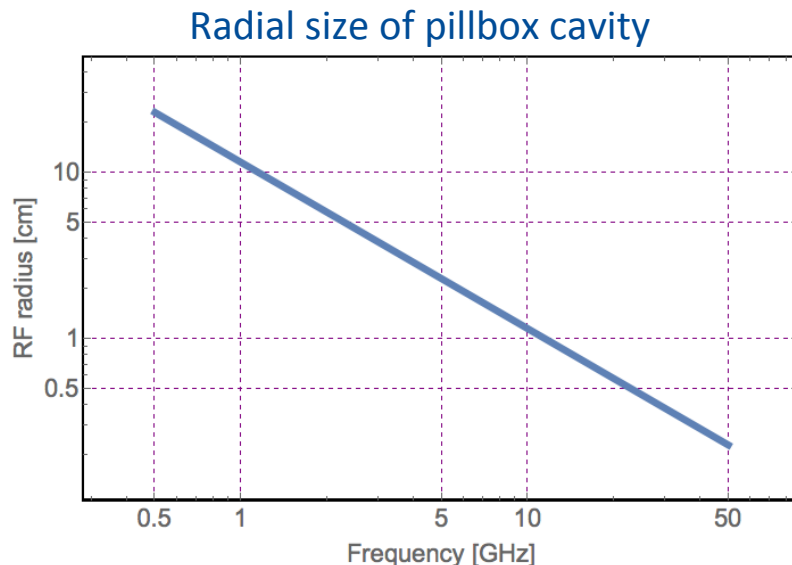
- Preliminary AC electric resistivity measurement will be done in Teslatron at Fermilab
- In order to meet the ADMX operation parameter, other AC electric resistivity measurement will be carried out at the National High Magnetic Field Lab in Florida



- A compact resonator will be made
- Above pictures are a superconducting 1.86 GHz Coplanar Waveguide Resonator
- Size of resonator part is only a few mm

# Make prototype cold RF resonator

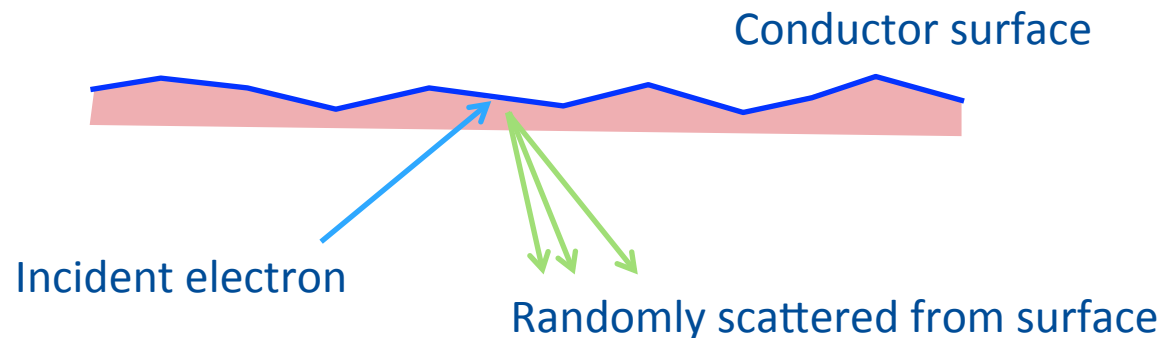
- Make a prototype resonator in which the resonant frequency can be 2 GHz – 20 GHz
- Demonstrate feasibility of a large volume high-Q resonator
  - Develop surface treatment technologies including with metallic coat, SRF surface polishing, and annealing processes
- Test will be done at NHMFL and/or Mucool Test Area





# Require systematic investigation of surface condition

- Surface condition is particularly important to reduce the surface resistivity (when the mfp of electron is longer than surface roughness)



- Control roughness
  - Make smooth by annealing at 773 K (melting point of Al 993 K)
  - Electro-polishing, chemical rinsing, etc
- Thickness

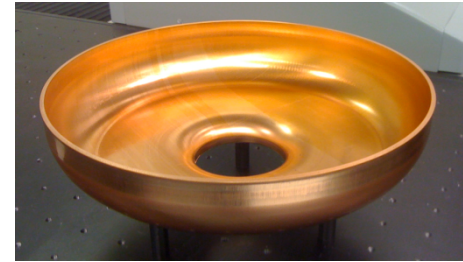
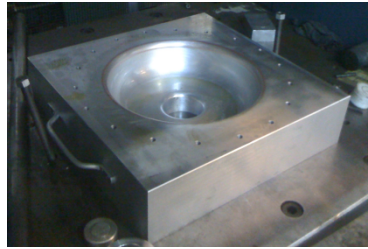
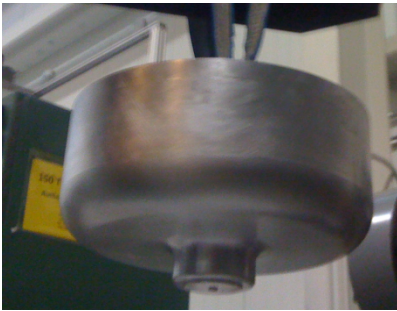
## Two possible ways to fabricate Al-based resonator

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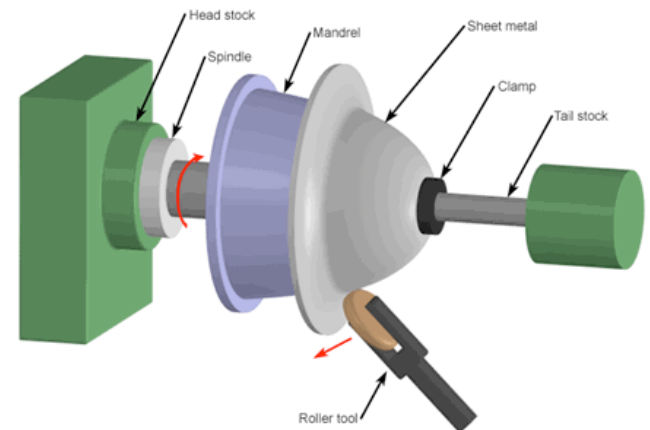
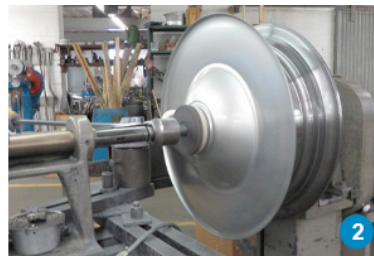
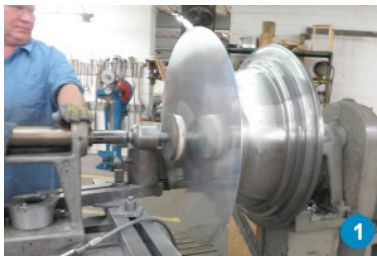
- Use a thin aluminum sheet and form a resonator shape
- Make a thin aluminum film by vacuum deposition

# Fabricate Al-base RF resonator by using SRF technique

- Conceive manufacturing as for SRF cavities, i.e. using deep-drawing to produce half cells
- Tune half cell by trimming equator
- Join half cells by EBW



Or, since high purity aluminum is soft (like gold) we can apply metal spinning formation  
→ Advantage for seamless shape





# Vacuum Deposition Thin Film Coatings Facility at Lab 7

Thin Film Coating Facility in Particle Physics Department in Lab 7 at Fermilab



Available thickness will be limited

# Possible applications by using high-purity Al resonators

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- Accelerator cavity
  - High Secondary Emission Yield (SEY) induces a multipactoring in the resonator
  - It sucks up a huge RF power
  - Multipactoring may prevent by a thin-film-coating or putting buffer gas in the resonator
- Stabilizer for SC magnet
- Substrate for SRF
- Quantum electric circuit

# Summary

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- Propose high-purity aluminum resonator
  - High-purity aluminum has excellent property, particularly at low temperatures in strong magnetic fields
    - May be the best material for the axion detector resonator
  - There are many uncertainties to design for the resonator
  - Propose 3-yr project to find out material properties of high-purity aluminum
- Look for more collaborators